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PRINCIPAL INVESTIGATOR: Thomas J. Beck, Sc.D.

CONTRACTING ORGANIZATION: Johns Hopkins University
Baltimore, Maryland 21205-2196

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693 female U.S. Marine Corps recruits were studied with anthropometry and dual energy x-ray absorptiometry (DXA) scans of the thigh and lower leg prior to recruit training. A total of 37 stress fractures were confirmed. Female data were combined with an earlier study of 626 male Marine recruits including 38 stress fracture cases. Bone structural geometry, cortical dimensions, thigh lean mass and muscle cross-sectional area were derived from DXA data. Measurements were compared within sex between pooled fracture cases and controls. Fracture cases in both sexes were less physically fit, and had smaller thigh muscles compared to controls. After correction for body size, section moduli (Z) and bone strength indices of the femur and tibia were smaller in fracture cases of both sexes but patterns differed. Compared to controls, female cases had thinner cortices and lower BMD. Male cases had narrower bones but similar cortical thickness and BMD. In both sexes, differences suggest poor skeletal adaptation to training in fracture cases due to inadequate prior conditioning. Lower stress fracture rates in African Americans compared to whites or Hispanics suggest stronger bones. Ethnic differences in bone and muscle indices of fracture susceptibility were studied within sex, using pooled data compared among ethnic groups. African Americans of both sexes showed longer leg bones, narrower pelves, larger tibia Z's, leaner thighs and larger thigh muscles than other groups, although initial fitness levels were similar (males) or worse (females). Differences suggest genetically stronger skeletal mechanics in African Americans, compared to other groups. Results imply that stress fracture susceptibility and bone strength have both environmentally plastic and genetic components.

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TABLE OF CONTENTS

INTRODUCTION

Strenuous weight bearing activities cause bending and torsion of bones, particularly in the lower limbs. Continued repetition of these activities can lead to stress fracture. Stress fracture is a costly problem for military recruits as well as for elite runners and dancers hence better understanding of the phenomenon and improved prevention methods are desirable from both clinical and economic vantages. Studies of stress fracture susceptibility may also provide insight into more generalized factors influencing bone strength.

Mechanistically, stress fracture results from a form of fatigue damage. Fatigue damage is a local microstructural disruption of the material that can progress to complete failure with repeated loading cycles. Bone and other structural materials have an endurance limit, a level of stress below which no damage will occur, regardless of the number of loading cycles applied(1). Conceptually one might eliminate stress fracture by reducing the number and magnitudes of loading cycles, so that either stresses remain below the endurance level or rarely exceed it. If all individuals were identical, then this should be achievable by calibrating the training conditions. In military training facilities, training conditions can be considered to be reasonably uniform, nevertheless stress fractures occur in 5-7% of trainees in elite programs suggesting that some individuals are more susceptible than others. There is evidence that individual differences may be structural in nature, resulting in proportionally higher mechanical stresses under loading in fracture cases.

Studies of Israeli Army Recruits using radiographic methods showed higher stress fracture rates in those with narrower tibias(2), and smaller tibia medio-lateral cross-sectional moments of inertia(3). In a previous study of male US Marine Corps recruits using a dual energy x-ray absorptiometry (DXA) method, we similarly found that stress fracture cases had lower medio-lateral cross-sectional moments of inertia and section moduli in both the distal third of the tibia and the mid-shaft of the femur(4). Fracture cases in our male study were also physically smaller (i.e., smaller body weight and anthropometric dimensions) on average, suggesting that greater stresses might also be due to proportionately higher loading forces where smaller recruits carry the same pack loads as larger recruits. However, when bone shaft geometries were corrected for body size (weight) diaphyseal dimensions remained significantly smaller in fracture cases, while joint dimensions were not different[4]. Because diaphyses are more environmentally labile than articulations[5], this suggested that stress fractures could result from poorer physical conditioning, and thus weaker diaphyses, prior to recruit training.

Individual differences in stress fracture susceptibility may also have intrinsic or genetic components. Several stress fracture studies have shown that fractures are more common in females and are relatively rare in African Americans [6, 7]. One might infer that African Americans have stronger bones than whites, and that male bones are stronger than female bones. A similar inference is usually drawn from osteoporosis studies in the elderly where bone mass is lower and fracture rates higher among whites and females compared to males and African Americans, respectively. The ethnic breakdown of stress fracture cases for Hispanics, African Americans and whites of both sexes among US Marine Corps recruits[†] are shown in Figure 1. Note that like hip fracture rates in the elderly, stress fractures are more common in females compared to males, and are more common in whites than in African Americans. Among Hispanics, the male stress fracture rate is similar to that of whites but in females is significantly higher.

The present study consists of a prospective analysis of female Marine Corps Recruits to which we compare the previously described male data set [4] supplemented with additional fracture cases. DXA based methods are again used to derive measures of bone geometry. The geometry measurements are extended to include estimates of cortical thickness and additional indices of bone strength.

We also included measures of DXA derived muscle mass and physical conditioning. While not readily obvious, in addition to weaker bones, increased mechanical stress may also result from weaker muscles. Not only are forces on bones mainly mediated through muscle contraction[4], but certain muscle groups function to oppose bending and torsional stresses under load. Weaker muscles may possibly fatigue more easily thus degrading this protective function under repetitive loading. There is also evidence from previous reports that fracture cases are relatively less physically fit

† Richard N. Shaffer LCDR, USN, Personal communication, unpublished data based on 4203 males and 2651 females in the three main ethnic groups from USMC recruit depots at Parris Island SC (females) and San Diego CA (males).

[8]. We measured relative thigh muscle mass and used it with thigh girth to compute an estimate of muscle cross-sectional area as an index of muscle strength. In addition, estimates of body fat content were derived from anthropometry measurements, and physical fitness data on recruits were extracted from military records.

In this paper we concentrate on characterizing the biomechanical differences between stress fracture cases and controls. We also examine how these indices differ between the sexes and among whites, African Americans and Hispanics to determine if they are consistent with rates of stress fractures in these groups.

BODY

MATERIALS AND METHODS

Subjects:

The study design was prospective; Marine Corps recruits were enrolled after appropriate IRB approval for human subject research. Female recruits were studied at the Parris Island Recruit training facility in Beaufort SC, between June, 1995 and September, 1996. Recruit volunteers were given a consent form during the first week of training and then administered a questionnaire on general background information (diet, exercise, menstrual and smoking histories, and previous skeletal injury) for the purposes of a larger separate study. A subset of these recruits was given a second informed consent to participate in a study involving DXA scans and anthropometry. A randomly selected sample of volunteers was then enrolled for further measurements. At the end of data accrual in September 1996 a total of 693 female recruits were enrolled for anthropometric measurements. Of these recruits, 671 received DXA scans. Enrollees ranged in age from 17 to 32 years with an average age of 19 years.

The previously described male study group of 624 enrolled subjects [4] ranged in age from 17 to 28 years, with an average age of 19 years. To improve case statistics, additional male fracture cases were added from a subsequent sub-study conducted in June 1994 over the same time period and location as our previous work. In the sub-study, a streamlined version of the project enrollment was followed where some anthropometry measures were not included, and DXA scans were done only on the thigh. Because some pre-screening criteria were used in sub-study enrollment, "normal" subjects were not necessarily representative and were not used here.

The female cohort was followed through the 12 weeks of training to ascertain the incidence of stress fractures and other musculoskeletal injuries, discovered by self-referral to sick call. Since self-referral resulted in a 40% under-reporting of stress fractures in our male study(4), a follow-up procedure was conducted at the end of training to determine whether the actual stress fracture rate differed from that self-reported to sick call.

Anthropometric Measurements:

Anthropometric measurements included height, weight, and girths of the neck, waist, hip (females only), thigh and calf. Lengths were measured of the upper and lower right leg, and medio-lateral widths were measured on the pelvis between the iliac crests, the hips between the greater trochanters (females), and the right knee at the level of the femoral condyles. An estimate of body density in males was obtained from height and girth measurements of the neck and waist(9), and for females, from height and girths of the neck, waist and hip(10). These estimates were then used with the Siri equation(11) to estimate total body fat.

Physical Fitness Data

Military records obtained on enrolled recruits included physical fitness scores based on numbers of repetitions of certain exercises and times recorded to run a specific distance, recorded during the first week of training. Midway during the female study, the run distance requirement for the initial strength test was increased from 0.75 to 1.5 miles. This made female scores difficult to interpret, hence for the purposes of this study, run scores were taken instead from the 1.5 mile run recorded after two weeks of training.

Bone Measurements:

DXA scans were done with a conventional Norland XR26 scanner (Norland Medical Systems Inc., Fort Atkinson WI) at both the mid-shaft of the right femur and at one-third the length of the lower right leg from its distal end(4). A scan speed of 10 mm/s with a data spacing of 0.5 mm was used in the scanner "research" mode for a total of 10-12 scan lines traversing the bone(s) at each location. Using programs described previously (4) DXA image data were used to derive medio-lateral bone widths, cross-sectional areas (i.e., cortical-bone-equivalent surface area) and cross-sectional moments of inertia, of the femur, tibia and fibula at the scan locations described above. In addition, the "whole bone strength index", after Selker and Carter (12), was calculated as the ratio of section modulus to bone length. This index is based on the observation that strength of a bone under bending or torsion is inversely dependent on bone length and directly related to the section modulus. In order to make units more convenient bone strength indices were multiplied by 100. As before(4), section modulus was calculated as the ratio of cross-sectional moment of inertia to half of the medio-lateral bone width. Since critical failure may also be related to cortical dimensions, estimates of mean cortical thickness were obtained as well. Because DXA scan resolution is inadequate for direct measurement of inner cortical dimensions, an indirect estimate of mean cortical thickness (t_b) for an equivalent circular annulus was computed as:

$$t_c = \frac{w}{2} - \sqrt{\left(\frac{w}{2}\right)^2 - \frac{A}{\pi}} \qquad [1]$$

where w is the measured medio-lateral bone width and A is the cortical equivalent cross-sectional area. The right part of expression [1] is an estimate of the endosteal radius. Conventional BMD was also derived individually for the femur, tibia and fibula from the same bone mass data.

Muscle Measurements

The standard Norland software was employed to measure lean and fat muscle mass for the soft tissues within the thigh scan field. The measurement was expressed as relative lean mass, i.e. the ratio of lean to total soft tissue mass within the region-of-interest. While the muscle measurement could have been done at both the thigh and lower leg, the distal location of the latter region, which excluded major muscle (belly) groups, made it difficult to interpret.

Muscle strength can be quantified by physiologic cross-sectional area(13); a quantity based on knowledge that strength of a muscle bundle is a function of the number and lengths of muscle fibers within the muscle organ. Because muscle fiber length could not be readily obtained in these subjects we derived a muscle cross-sectional area in the thigh (A_m) as a surrogate. A_m was obtained as the product of thigh soft-tissue cross-sectional area and the relative lean mass fraction. Thigh soft tissue cross-sectional area was derived from measured thigh girth after subtracting the total cross-sectional area of femoral bone obtained from its diameter. Both the thigh and femur were assumed to be circular for this purpose.

Ethnic Differences

Among the male and female study populations, 94% and 93% respectively were white, African American or Hispanic. Among females 447 (64.5%) were white, 119 (17.2%) were African American and 76 were Hispanic. Males in those groups consisted of 425 whites, 43 African Americans* and 133 Hispanics. Differences between these three groups, pooled after excluding other ethnic groups, were compared within sex.

Statistical Analysis

Statistical analysis of results was done with StatView for the Macintosh (Version 5.0 - SAS Institute Inc., Carey, NC). Adjusted means of pooled data within sex were computed in StatView using residuals from the multiple regression on height and weight, summed to the average value of the parameter. Differences between fracture cases and controls were examined by a two-tailed student's t test, while differences between ethnic groups were tested by Tukey/Kramer post-hoc analysis.

RESULTS

Fracture Incidence

As in the previous study, fracture case definitions conformed to strict ICD-9-CM Expanded Orthopaedic criteria(4). A total of 37 females suffered stress fractures during the training period, corresponding to a fracture rate of 5.3%. Unlike the male study group, no additional fractures were discovered in active follow-up, indicating that self-reporting of stress fracture was accurate in fe-

* Male recruits are trained at both San Diego CA and Parris Island SC, while female recruits are only trained at the latter facility. The largest ethnic minority at the west coast facility, where we carried out our study of males is Hispanic while African Americans make up the largest minority group at Parris Island.

males. Of the 37 female recruits with fractures, 11 fractured at two sites, and one recruit suffered four stress fractures. For classification purposes, fractures were categorized as: pelvic girdle (including sacrum), femur, lower leg (tibia or fibula), and foot (tarsals or metatarsals). A total of 13 females had at least one stress fracture of the foot, and 10 each had at least one stress fracture of the pelvic girdle, lower leg or femur. Of the fractures in the pelvic girdle, one was in the sacrum while the remainders were located in the inferior or superior pubic ramii. Because fracture incidence was low, cases were pooled and all measured parameters were compared with those of non-fracture cases. In addition to stress fractures, a total of 37 recruits were diagnosed with shin splints or other skeletal stress reactions, six of whom were later diagnosed with stress fracture. Consistent with the male study, subjects with shin splints were excluded from the control group(4). This left a total of 626 female recruits diagnosed with neither stress fracture nor shin splints for comparison with 37 fracture cases.

The new male sub-study yielded a total of 15 additional stress fracture cases, four of which were located in the tibia, and 11 in the foot. Together with the 23 previously reported cases(4), a pooled total of 38 male recruits with stress fractures were available for comparison with the original 587 male controls after exclusion of 16 cases of shin splints. The 38 male stress fractures included 41% in the foot, 40% in the lower leg and 19% in the femur. Interestingly, above-the-knee fractures constituted nearly half (46%) of observed cases in females but only 19% in males, none of which was in the pelvis.

Twenty-seven male and twenty-eight female fracture cases were white (71% and 76% of totals, respectively). No male African American fractures were recorded in this sample, while 3 (8%) of the female cases were African American. Ten of the male cases (26%) were Hispanic, as were 5 female cases (14%). Because of the small number of fractures in some sex/ethnicity subgroups, differences between fracture and controls were not analyzed within ethnic groups. However, differences between ethic groups in physical characteristics are examined in a later section and related to fracture rates within these groups. The following section compares the physical characteristics of fracture and control subjects, by sex, with pooled ethnicity groups.

Fracture Cases versus Controls, Pooled Ethnicity

Anthropometric variables and physical fitness:

Means and standard deviations for age and anthropometric and fitness variables in cases and controls of both sexes are given in Table 1. As we found previously for male stress fracture cases(4), females with stress fracture were on average smaller in height, weight, and most dimensional measurements; but unlike their male counterparts, differences were slight and did not reach statistical significance (Table 1).

With the addition of 15 additional cases to the male data, the same anthropometric variables that were significantly smaller in fracture cases in our earlier study remained significant, but magnitudes of differences in height, weight, BMI (weight in kg/(height in m)^2) and most girth dimensions were somewhat smaller than those reported previously(4). Pelvic widths as an index of skeletal size were smaller in male cases than in controls but not significantly different in females, while bicondylar breadth, a measure of joint size was essentially identical in cases and controls of both sexes.

Percent body fat content (Table 1) as estimated from anthropometric dimensions was lower in fracture cases of both sexes but did not reach statistical significance in either sex. As shown in Table 1, stress fracture cases were on average, able to do fewer sit-ups and run times were significantly longer. Taken together with the observations on thigh muscle measurements (see below), stress fracture cases appear to have weaker thigh muscles than non fractured controls, and consistent with previous reports(8), are significantly less physically fit.

Bone Geometry and Mass Variables

The average values of femoral and lower leg bone geometry are compared between cases and controls of both sexes in Table 2. Dimensions are reported in powers of cm to facilitate comparison with literature values. Also male cross-sectional measurements were linearly scaled to correct a calibration error in the original work(4). Since the correction applied equally to all subjects it had no bearing on previous conclusions, but absolute values of bone cross-sectional areas and moments of inertia were reduced by 39%. Since the additional male cases were not scanned in the lower leg, the tibia and fibula values are as reported previously (after scaling correction and conversion to cm)(4) but strength indices and cortical dimensions have been added. Femur averages reflect the larger set of 38 male fracture cases.

Conventional BMD is significantly smaller in fracture cases for all three bones in both sexes as are many of the geometric variables. For most variables, differences between cases and controls are greater in males than females. This observation is misleading since bone geometry is clearly body size dependent and male fracture cases showed a greater size discrepancy from controls than did females. In males we previously found that body weight was the best single descriptor of body size, with the highest correlations with skeletal geometry compared with other anthropometric measurements. The same finding was observed here in females. Coefficients of determination from regressions of geometric dimensions and BMD on body weight explained from 4% to 52% of the measured variance in those variables; all correlations were significant at the $p < 0.05$ level. Correlations with height were also significant, though weaker in most of the measured parameters. We therefore decided to adjust bone and muscle measurements using the residuals from the multiple regression on height and weight, summed to the average value of the parameter within sex.

Because the fibula carries little body weight, body size-related variations are difficult to interpret. Composite sectional properties of the tibia and fibula while possible were not attempted due to uncertainty in the relative positions of the bones in a single projection image. Observed correlations of height and weight with fibula measurements were also weaker than with the femur and tibia. To simplify interpretations, fibular dimensions were excluded from further analyses.

After adjustment for body size, one male fracture case with both body mass index (BMI) and percent body fat in the 99th percentile (31.4 kg/m^2 and 30% respectively) appeared to skew the size adjusted tibia averages. This subject, who suffered one of the few male femoral stress fractures, had an adjusted tibia strength index that was 2.4 standard deviations above that of male controls. Consistent with his fracture location, however, his adjusted femoral strength index was lower, within a standard deviation of control values, although higher than the average of fracture cases. Because his adjusted tibia values appeared to be inconsistent with other fracture cases, his tibia (only) measurements were excluded from adjusted means. Height and weight adjusted means are compared between cases and controls in Table 3.

Interestingly, size adjusted male but not female fracture cases have wider pelves and longer femora than controls, while tibia lengths are similar. Size adjusted differences in joint size as indicated by bicondylar breadth remain non-significant for both sexes (Table 3).

Many of the bone measurements that differed in the unadjusted data (Table 2) remain significantly different between cases and controls after adjustment for body size. BMD differences in males are eliminated by size correction but this is not the case in females. This apparent anomaly becomes clearer with a closer look at adjusted cortical dimensions (Table 3). Only female cases show thinner cortices; male cases show somewhat narrower periosteal diameters, but little difference in cortical thickness. Thus, the percentage of cortical bone within the periosteal envelope is smaller in female cases, but not in males, leading to a significant reduction in BMD in female fracture cases. Bone strength, as depicted by section modulus or bone strength index, is smaller in fracture cases of both sexes. The reduced strength in females is due to smaller cortical thickness, while in males it is due to narrower periosteal diameter. Note that a longer femur length is a contributor to lower bone strength indices in male fracture cases, while in the tibia and in both bones of females, lower strength indices are due only to lower section moduli.

Muscle Measurements

In females, but not males, the uncorrected lean muscle mass at the thigh is significantly smaller (Table 2) in fracture cases. However, when thigh muscle cross-sectional areas were computed, differences between cases and controls in both sexes are significant. After correction for body size (Table 3), essentially the same differences are observed. Differences between cases and controls for thigh muscle cross-sectional area decrease in magnitude after body size adjustment but remained significant. This indicates that muscles are relatively smaller in cases after correction for body size, consistent with the findings of smaller bone geometries and poorer fitness levels.

Ethnic Differences, Pooled Cases and Controls

Anthropometric variables and physical fitness:

Average values of age, anthropometric dimensions, and physical fitness for the pooled sample (fracture and shin splint cases + controls) of the three main ethnic groups broken down by sex are shown in Table 4. Subject ages were essentially identical across ethnic groups, but there were a number of anthropometric and dimensional differences in both sexes. African Americans were similar in height, weight and BMI, but had lower body fat, smaller waists, narrower pelves and relatively longer thighs and tibiae, compared to whites. Although the differences do not all reach significance, Hispanics of both sexes tended to be lighter and shorter in stature than whites or African Americans, with higher BMI's and body fat content. Breadths of the pelvis were similar in whites and Hispanics of both sexes but narrower in African Americans. In females, trochanteric breadth was narrower in Hispanics and African-Americans compared to whites. Among Hispanics, thigh lengths were shorter than those of whites or African Americans in both sexes; tibia lengths were similar to whites in females but shorter in males.

Exercise scores based on numbers of sit-ups were similar in all groups but longer run times (not significant in males) are suggestive of poorer initial physical condition in African Americans relative to whites or Hispanics.

Bone and Muscle Variables

Height and weight-adjusted means for pelvic width, bone lengths, geometries and muscle parameters are listed in Table 5, broken down by sex and ethnicity. Note that in both sexes, adjusted pelvic widths are narrower in African Americans compared to whites or Hispanics. In males, femurs and tibias are longer in African Americans, and similar in whites and Hispanics. Adjusted thigh lengths in African American and Hispanic females were similar but longer than those of white females. Also among females, tibias are longest in African Americans, intermediate in Hispanics and shortest in whites.

With respect to bone cross-sectional geometry and BMD in both sexes, ethnic differences are greater in the tibia than in the femur. In the female femur, African Americans and whites BMD and geometry values are quite similar although in the tibia, BMD, cortical area, periosteal width and section modulus are higher than those of whites. African American females have similar tibia widths but thicker cortices compared to Hispanics. In both bones, Hispanic females show lower values of BMD, cortical thickness and strength index (not significant in femur) compared to whites. Note that in this case the lower femur strength index in Hispanic females is due to both longer femurs and (non significantly) smaller section moduli. In the male, differences between African Americans and whites are unremarkable in the femur but in the tibia, cortical area, CSMI and section modulus are greater in African Americans. In the male Hispanic, the geometric differences from whites are less apparent in the tibia than in the femur, where strength index and cortical areas are smaller in Hispanics. Note that in both sexes and both bones (not significant in the femur) African American show higher section moduli than the other two groups but the differences are largely offset in the strength indices by longer bones. Thighs of African Americans of both sexes are leaner, with significantly larger muscles than those of whites or Hispanics.

These differences do not all reach statistical significance, but are generally suggestive of higher bone and muscle strength in African Americans and lower bone and muscle strength in Hispanics, relatively to whites. Interestingly the ethnic differences are greater in the tibia in some comparisons and in the femur in others.

DISCUSSION

Stress fracture may be considered as a case of structural failure of bone, thus should be amenable to biomechanical explanation. Here we have attempted to supplement bone mass measurements with quantities having intrinsic biomechanical meaning, in an attempt to provide more direct insight into differences in bone strength. The results of this study support the growing body of evidence for the hypothesis that stress fracture occurs because fracture cases experience relatively higher skeletal stresses than do those who do not fracture. It is also not surprising that there appear to be both bone and muscle components of these higher mechanical stresses.

In our previous paper we noted that male fracture cases were relatively smaller in body size than controls, although the addition of 15 more cases to that male group reduced body size differences. These size differences were also not apparent in female stress fracture cases when compared with controls. We had previously hypothesized that the greater stress fracture rate in smaller individuals resulted from relatively higher stresses due to a greater incremental loading when carrying the same backpack loads. This conjecture may still play a part, but reduced size differences with a larger male case sample, and the fact that female cases were not significantly smaller, would suggest that the role of body size is a minor one. The observation that tibia and femoral section moduli and strength indices were smaller in fracture cases is, however, consistent with our earlier work(4) as well as that of Giladi(2, 3, 14) and colleagues. The fact that these geometric differences remain after correction for body size (height and weight), and that the knee joints (bicondylar breadth) of cases are not different, would suggest that cases have long bone geometries that are less well suited to resist the mechanical stresses of intense physical training. An important question is whether these bone strength differences are environmentally determined, i.e., lack of adaptation to the anticipated levels of mechanical stress encountered in military training, or genetically predisposed. Here, there appears to be fuel for the argument that bone strength differences have both environmental and genetic factors.

Marine Corps recruits in these cohorts had an average age of 19 in both sexes; an age at which long bone joints have generally reached adult dimensions and can no longer adapt to environmental changes in skeletal loading. Indeed they are not different between cases and controls in these data. The shafts of long bones however, retain the ability to adapt to changes in loading through adult life(5). The mechanical stresses generated in long bones from physical activity are dominated by dynamic stresses due to bending and torsional loads(15). Attached muscles acting to move the body against gravitational forces produce these dynamic stresses(16). Generalized models of physical adaptation of long bones as proposed by Beaupre et al (17) and later refined by van der Meulen et al (18) assume that bones adapt to produce stress magnitudes corresponding to a specific normal range of strains, consistent with the "mechanostat" of Frost(19). These generalized models are based on the view that the maximum strain that can be generated in a given bone is proportional to the strength of the muscles acting on that bone. These necessarily simplified models assume that muscle strength scales with body weight. Our data generally support this simplification since section moduli and bone strength indices at scan locations are well correlated with body weight in both sexes, ($r^2 = 0.3$ to 0.5). Clearly, however, similarly sized individuals vary in muscle strength, and if muscle forces are indeed the osteogenic stimulus for adaptation, those with weaker muscles should also have weaker bones. Here we see that after correcting for body weight, stress fracture cases of both sexes not only have smaller bone geometries but also smaller thigh muscle cross-sectional areas and are in poorer physical condition. Smaller muscle cross-sectional areas would generate lower peak forces consistent with the smaller bone geometries in fracture cases.

The sex differences in cortical geometry, where female cases have relatively thinner cortices and male cases have relatively narrower periosteal diameters, are interesting from a developmental perspective. There is evidence that the periosteal surface of long bones is most sensitive to alterations in mechanical loading during childhood and early adolescence, but the endosteal surface is more sensitive thereafter[(20)]. This difference may be related to more general developmental changes in bone modeling/remodeling that occur during adolescence. These changes occur earlier in females than in males [(21)]. While males and females in our study were the same absolute age (Table 1), the female skeleton may be relatively more developmentally advanced. Thus if physical inactivity explains at last part of the smaller bone dimensions in our fracture subjects, then it is possible that this had more of an effect on the endosteal surface of the more developmentally mature females, and on the periosteal surface of the less mature males. This conjecture is consistent with our geometric results. These results also caution against the use of BMD in mechanical interpretations, since a change in BMD may or may not be associated with a corresponding change in structural strength (also see Ruff and Hayes 1984)[(22)].

The fact that smaller muscles and poorer physical condition are associated with stress fracture is interesting from two standpoints. First, the smaller muscle forces could play a role in development of inadequate bone geometries, but secondly, weaker muscles may themselves lead to higher bone stresses under repetitive loading. In recent work by Milgrom and colleagues rosette strain gauges were implanted on tibiae of 5 male and 3 female military recruits and strain rates in free walking on a treadmill were recorded before and after a muscle fatiguing 2 km run[(23)]. In both sexes there was a significant increase in strain magnitudes and strain rates following the 2-km run, moreover the increase was greater in females than in males. This would suggest that muscles serve a protective role in resisting the normal stresses in bones. Contraction of a muscle attached to the terminal ends of a long bone may serve to resist bending in opposition, thus converting bending stresses to compressive stresses; bone is intrinsically stronger in compression than in tension or shear [(24)]. Muscle fatigue appears to diminish this protective function resulting in higher bone stresses.

If prior physical condition results in the bone and muscle changes that underlie stress fracture susceptibility, then one would expect that physical fitness levels among ethnic groups would correspond to their observed rates of stress fracture. Male Hispanics and whites have similar fitness levels and indeed their stress fracture rates are similar (Figure 1). Female Hispanics have a higher stress fracture rate than whites but their fitness levels also are similar. The observation that the physical fitness of African Americans was similar (males) or slightly worse (females) than those of whites, taken with their lower rates of stress fracture would suggest that genetics rather than physical conditioning may explain their apparently stronger bones. Despite ambiguous physical fitness data, there are differences in body size-adjusted lower extremity bone structure and musculature between the ethnic groups. While not strikingly clear, these differences are consistent with the ethnic patterns in stress fracture rates observed in this population (Figure 1).

Stress fracture appears to be associated with a wider pelvis in males (Table 3); African Americans have narrower pelves than whites or Hispanics (Table 5). Fracture susceptibility is also associated with smaller section moduli, and indeed this value is largest in African Americans of both sexes, although femur values do not reach significance. Longer bone length reduces bone strength; indeed male fracture cases (Table 3) had significantly longer femora. African Americans however, show longer tibias and femurs (Table 5), which when combined with the section modulus in the strength index, reduce values to similar or slightly larger (not significant) to that of whites. The only statistically significant ethnic differences in strength index, were seen in the smaller values relative to whites in the femurs of Hispanics of both sexes. This observation is consistent with the higher Hispanic stress fracture rate in females but is not consistent with the rate in males.

Perhaps the most interesting ethnic differences are in the thigh muscle measurements. In both males and females the thigh lean fraction is higher and the muscle cross-sectional area is larger in African Americans compared to other groups. Thighs of Hispanic males were significantly less lean and had smaller muscle cross-sectional areas compared to whites or African Americans.

It seems likely that the explanation for the observed differences in stress fracture rates in the different ethnic groups may be due to a complex interplay of physical conditioning and genetically associated factors influencing both bone and muscle geometry.

There are a number of limitations of this work. First, like some other stress fracture studies(2, 3) the femoral and lower leg bone geometries were measured in a single plane and thus are relevant mainly to frontal plane stresses. Much of the dynamic loading of the lower limb produces stresses in the saggital plane(25). Another limitation of this work is that like a large fraction of bone mineral studies in the literature, skeletal measurements at one (technically convenient) anatomical location were used to infer bone strength at other locations. Moreover, our sample size of stress fracture cases was not large enough to permit separate analysis by fracture location. This assumes that bone measurements at the femur or tibia are representative of bone strength at other lower extremity locations. Certainly there is heterogeneity in the geometry between lower extremity locations in the same individual, and this methodology lacks the resolution to differentiate these differences. Conceivably a larger study, with more stress fracture cases could provide greater insight into bone strength differences between fracture sites.

Use of the DXA methods in this study illustrate that structural information is indeed present in bone mass data, though its implications are not always evident in the conventional presentation (as BMD). In fairness, current DXA scanners are better suited to measurement of BMD where dimensional errors are less problematic, than they are to the measurement of geometry. The dimensional differences between cases and controls in this study are quite small; for example, the relatively large 15% average difference in uncorrected male femoral sectional modulus (Table 2) was attributable to only 1 mm in periosteal breadth. Many other dimensional differences such as cortical thicknesses were much smaller. The coefficient of variation in bone widths with our measurement averaged about ±0.2 mm[4], it is therefore likely that the ability of current DXA technology to detect small differences in bone geometry in individuals would be limited. Also, while DXA scanners can be used to determine lean muscle mass, our measurement was rather crude and could be improved with better technology, and ad hoc software and calibrations.

CONCLUSIONS

The conclusions of this study are as follows:

- Stress fracture susceptibility appears to have both environmental and genetic components.
- Consistent with other reports[8], stress fracture cases are less physically fit than non-cases.
- Those who do not fracture in both sexes show significantly larger bone cross-sectional geometries consistent with stronger bones.
- Fracture cases of both sexes have smaller thigh muscles consistent with a role for muscle in stress fracture susceptibility.
- Higher fitness levels and larger muscle sizes in controls suggest that bone geometric differences are an adaptation response from the increased mechanical loading due to physical conditioning prior to the initiation of basic training.
- Female stress fracture cases show thinner cortices than controls but similar periosteal diameters, while male cases show narrow periosteal diameters but similar cortical thicknesses compared to controls. This may indicate a sex difference in the bone response to physical training where females respond by building bone on the endosteal surface while males respond on the periosteal surface.
- Ethnic differences in bone geometry and muscle size are suggestive of a genetic role in fracture susceptibility, particularly in explaining the lower fracture rates in African-Americans. African-Americans show significantly leaner thighs and larger thigh muscles compared to Whites despite a suggestion of poorer initial physical conditioning. African-Americans also show larger section moduli in the tibia indicating lower bending stresses, but this advantage may be offset by longer leg bones producing larger bending moments. The narrower pelves of African

Americans may also provide an unexplained mechanical advantage, as male fracture cases had significantly wider pelves compared to controls.

- Conventional bone mass measures (BMD) can obscure the underlying geometric changes responsible for differences in fracture susceptibility.
- The measurements of bone structural geometry and muscle, employed non standard analyses which be difficult to implement as a practical screening tool without improvements in scan precision and image spatial resolution. Precision is also limited by restriction of the data to a single plane since dimensional errors can result from variations in patient position since bones are not axially symmetric. Under a NASA sponsored contract we are developing a high resolution multiple projection DXA scanner specifically designed to measure the three dimensional structural geometry of long bones. The design would be well suited to the screening of subjects for stress fracture and to the quantification of musculoskeletal response to physical training.
- A number of scientific and practical questions remain.
  - Is it possible to detect a strengthening response in bone resulting from training? Poor precision and spatial resolution of the commercial DXA system prevented the successful detection of geometric changes in bones as a direct response to the training regimen. We continue to pursue this question using the same technology with sequential scan data from a larger study of US Naval Academy undergraduates. We hope that the larger study may permit such subtle changes to be extracted in the presence of poor precision, although ultimately better technology is needed.
  - We do not fully understand the interrelationships between muscle strength and bone strength. This has important implications in the etiology of stress fracture but also in understanding the interplay between physical activity and osteoporosis and fracture risk in the elderly.
  - How much and what kind of training would strengthen bone sufficient to prevent stress fracture?

- If a quick screening method is to be developed, what skeletal locations should be measured to best represent the risk of stress fracture and to best characterize lower limb strength?
- How do DXA derived measurements of muscle size correlate with objective measures of muscle strength? Can a practical, rapid muscle strength measurement be developed from DXA technology?

Table 1: Means and standard deviations of age, anthropometric dimensions and exercise scores in stress fracture cases and controls of both sexes.

Parameter	MALES						FEMALES					
	Controls (N=587)		Cases (N=38)				Controls (N=626)		Cases (N=37)			
	Mean	*SD*	*Mean*	*SD*	*Percent difference*	*Significance*	*Mean*	*SD*	*Mean*	*SD*	*Percent difference*	*Significance*
Age	19.28	±1.81	18.90	±1.80	-2.0%	(0.19)	19.07	±1.98	19.65	±2.82	3.1%	(0.09)
Weight (kg)	75.39	±11.0	70.27	±14.5	-6.8%	0.007	57.95	±7.20	55.89	±8.62	-3.6%	(0.10)
Height (cm)	175.04	±6.64	172.8	±6.72	-1.3%	0.046	162.8	±6.55	161.2	±6.04	-1.0%	(0.15)
BMI (kg/m^2)	24.58	±3.18	23.38	±3.81	-4.9%	0.027	21.83	±2.08	21.43	±2.52	-1.8%	(0.27)
Percent Body Fat	16.18	±5.60	15.39	±6.63	-4.9%	(0.40)	24.18	±4.36	23.31	±4.75	-3.6%	(.24)
Neck girth (cm)	38.59	±2.25	37.31	±2.33	-3.3%	0.0007	31.89	±1.54	31.72	±1.43	-0.5%	(0.53)
Waist girth (cm)	85.08	±8.61	82.63	±10.8	-2.9%	(0.095)	68.86	±5.16	67.76	±5.13	-1.6%	(0.21)
Hip girth (cm)	-	-	-	-	-	-	94.05	±5.45	92.63	±6.54	-1.5%	(0.13)
Pelvic width (cm)	28.46	±2.44	27.63	±3.14	-2.9%	(0.67)	27.94	±2.01	27.61	±2.05	-1.2%	(0.34)
Trochanteric width (cm)	-	-	-	-	-	-	31.63	±1.90	31.39	±2.18	-0.8%	(0.46)
Femur bicondylar breadth (cm)	10.45	±0.77	10.39	±0.79	-0.6%	(0.62)	8.94	±0.51	8.89	±0.43	-0.6%	(0.60)
Thigh length (cm)	52.17	±3.02	52.67	±3.42	1.0%	(0.33)	50.92	±3.06	50.55	±3.40	-0.7%	(0.48)
Tibia length (cm)	40.76	±2.47	39.74	±2.31	-2.5%	0.014	37.11	±2.35	36.52	±2.39	-1.6%	(0.14)
Leg length (cm)	103.86	±4.90	98.63	±5.77	-5.0%	0.0001	88.04	±4.89	87.07	±5.05	-1.1%	(0.25)
Thigh girth (cm)	54.51	±4.58	52.5	±5.86	-3.7%	0.0107	52.23	±3.99	51.80	±4.02	-0.8%	(0.58)
Calf girth (cm)	37.35	±2.74	35.87	±3.36	-4.0%	0.012	34.52	±2.25	33.80	±2.77	-2.1%	(0.11)
Numbers of sit-ups	57.2	±13.3	51.8	±10.8	-9.5%	0.022	35.0	±6.45	32.7	±6.64	-6.6%	0.05
Run-scores (seconds)	1086	±111	1157	±123	6.6%	0.0004	1215	±110	1269	±90.0	4.4%	0.007

Values in parentheses not significant at p =.05 level, in two tailed *t*-test.

Table 2: Means and standard deviations of thigh muscle, bone mass and geometric variables measured in the tibia, fibula, and femur for stress fracture cases and controls (pooled ethnicities). Fracture case values for male tibia and fibula are based on an N of 23.

Parameter	MALES						FEMALES					
	Controls (N=587)		Cases (N=38)				Controls (N=626)		Cases (N=37)			
	Mean	*SD*	*Mean*	*SD*	*Percent difference*	*Significance*†	*Mean*	*SD*	*Mean*	*SD*	*Percent difference*	*Significance*†
Tibia BMD (g/cm^2)	1.529	±0.146	1.443	±0.132	-5.6%	0.0057	1.442	±0.156	1.349	±0.139	-6.4%	0.0007
CSA (cm^2)	2.016	±0.261	1.797	±0.246	-10.9%	0.0001	1.650	±0.229	1.506	±0.210	-8.7%	0.0003
Periosteal diameter (cm)	2.174	±0.168	2.05	±0.130	-5.7%	0.0005	1.887	±0.156	1.841	±0.162	-2.4%	(0.086)
Endosteal diameter (cm)	1.467	±0.194	1.384	±0.128	-5.7%	0.042	1.203	±0.195	1.21	±0.192	0.6%	(0.85)
Mean cortical thickness (cm)	0.354	±0.043	0.333	±0.036	-5.9%	0.021	0.342	±0.049	0.316	±0.042	-7.6%	0.0024
CSMI (cm^4)	0.795	±0.218	0.631	±0.185	-20.6%	0.0004	0.482	±0.139	0.419	±0.127	-13.1%	0.008
Z (cm^3)	0.721	±0.142	0.609	±0.132	-15.5%	0.0002	0.504	±0.106	0.450	±0.097	-10.7%	0.0032
Bone Strength Index (x100)	1.768	±0.323	1.547	±0.327	-12.5%	0.0014	1.352	±0.255	1.231	±0.251	-8.9%	0.0071
Fibula BMD (g/cm^2)	0.821	±0.099	0.760	±0.090	-7.4%	0.004	0.790	±0.096	0.752	±0.085	-4.8%	0.027
CSA (cm^2)	0.584	±0.103	0.525	±0.095	-10.1%	0.0072	0.515	±0.089	0.493	±0.095	-4.3%	(0.3)
Periosteal diameter (cm)	1.175	±0.159	1.138	±0.147	-3.1%	(0.28)	1.077	±0.143	1.078	±0.140	0.1%	(1.0)
Endosteal diameter (cm)	0.792	±0.187	0.789	±0.165	-0.4%	(0.95)	0.706	±0.167	0.730	±0.143	3.4%	(0.4)
Mean cortical thickness (cm)	0.191	±0.032	0.174	±0.026	-8.9%	0.012	0.186	±0.030	0.174	±0.023	-6.5%	0.028
CSMI (cm^4)	0.0649	±0.029	0.0546	±0.022	-15.9%	(0.091)	0.046	±0.018	0.042	±0.016	-8.7%	(0.3)
Z (cm^3)	0.1068	±0.031	0.0931	±0.026	-12.8%	0.036	0.082	±0.022	0.076	±0.020	-7.3%	(0.16)
Bone Strength Index (x100)	0.262	±0.073	0.237	±0.063	-9.5%	(0.1)	0.221	±0.058	0.209	±0.054	-5.4%	(0.3)
Femur BMD (g/cm^2)	2.158	±0.189	2.073	±0.315	-3.9%	0.034	1.939	±0.162	1.829	±0.147	-5.7%	0.0001
CSA (cm^2)	3.252	±0.417	3.015	±0.463	-7.3%	0.0008	2.590	±0.305	2.371	±0.279	-8.5%	0.0001
Periosteal diameter (cm)	2.483	±0.194	2.371	±0.205	-4.5%	0.0006	2.202	±0.153	2.136	±0.134	-3.0%	0.011
Endosteal diameter (cm)	1.416	±0.238	1.329	±0.242	-6.1%	0.030	1.240	±0.055	1.239	±0.046	-0.1%	(1.0)
Mean cortical thickness (cm)	0.534	±0.065	0.521	±0.077	-2.4%	(0.24)	0.481	±0.193	0.448	±0.156	-6.9%	0.0005
CSMI (cm^4)	1.661	±0.440	1.408	±0.409	-15.2%	0.0006	1.031	±0.247	0.891	±0.190	-13.6%	0.001
Z (cm^3)	1.32	±0.251	1.168	±0.252	-11.5%	0.0003	0.927	±0.161	0.828	±0.126	-10.7%	0.0004
Bone Strength Index (x100)	2.519	±0.436	2.214	±0.406	-12.1%	0.0001	1.818	±0.295	1.652	±0.251	-9.1%	0.001
Thigh Lean Mass Fraction	0.885	±0.057	0.887	±0.083	0.2%	(0.83)	0.764	±0.061	0.734	±0.053	-3.9%	0.005
Thigh Muscle Cross-Sectional Area (cm^2)	205.3	±29.5	188.6	±32.2	-8.1%	0.0010	169.2	±22.5	159.0	±23.3	-6.0%	0.021

†Values in parentheses not significant at p =.05 level, in two tailed *t*-test.

Table 3: Means and standard deviations of tibia and femur geometries, pelvic and bicondylar widths and muscle parameters after correction for height and weight (pooled ethnicities). Male tibia values exclude stress fracture case with the highest BMI and % body fat (see text).

	MALES						FEMALES					
	Controls (N=587)		Cases (N=38)				Controls (N-626)		Cases (N=37)			
Parameter	*Mean*	*SD*	*Mean*	*SD*	*Percent difference*	*Significance*†	*Mean*	*SD*	*Mean*	*SD*	*Percent difference*	*Significance*†
Pelvic Breadth	28.41	±2.07	29.23	±1.98	2.9%	0.018	27.92	±1.61	27.85	±1.60	-0.3%	(0.78)
Femur Bicondylar Breadth	10.44	±0.614	10.58	±0.463	1.3%	(0.16)	8.93	±0.384	8.97	±0.315	0.4%	(0.57)
Thigh length (cm)	52.1	±2.220	53.4	±2.134	2.5%	0.0006	50.9	±2.152	51.0	±2.541	0.3%	(0.66)
Tibia length (cm)	40.7	±1.652	40.3	±1.341	-1.0%	(0.15)	37.1	±1.472	36.9	±1.264	-0.4%	(0.54)
Tibia BMD* (g/cm^2)	1.527	±0.125	1.493	±0.096	-2.2%	(0.22)	1.441	±0.146	1.365	±0.127	-5.3%	0.0028
CSA* (cm^2)	2.01	±0.194	1.912	±0.123	-4.9%	0.018	1.647	±0.193	1.544	±0.179	-6.3%	0.0022
Periosteal diameter * (cm)	2.172	±0.147	2.103	±0.095	-3.2%	0.031	1.885	±0.137	1.864	±0.144	-1.1%	(0.37)
Endosteal diameter (cm)	1.465	±0.187	1.412	±0.129	-3.6%	(0.19)	1.202	±0.185	1.226	±0.182	2.0%	(0.45)
Mean cortical thickness* (cm)	0.353	±0.038	0.345	±0.029	-2.3%	(0.34)	0.342	±0.047	0.320	±0.039	-6.5%	0.0064
CSMI* (cm^4)	0.791	±0.172	0.714	±0.091	-9.7%	0.039	0.480	±0.116	0.442	±0.105	-7.9%	(0.058)
Z* (cm^3)	0.719	±0.109	0.666	±0.061	-7.4%	0.024	0.502	±0.087	0.468	±0.081	-6.8%	0.0240
Bone Strength Index* (x100)	1.765	±0.267	1.641	±0.159	-7.0%	0.031	1.350	±0.229	1.262	±0.216	-6.5%	0.0287
Femur BMD (g/cm^2)	2.154	±0.161	2.145	±0.135	-0.4%	(0.78)	1.937	±0.144	1.852	±0.126	-4.4%	0.0006
CSA (cm^2)	3.241	±0.287	3.151	±0.219	-2.8%	(0.059)	2.585	±0.234	2.432	±0.201	-5.9%	0.0002
Periosteal diameter (cm)	2.479	±0.153	2.423	±0.146	-2.3%	0.031	2.200	±0.127	2.162	±0.103	-1.7%	(0.077)
Endosteal diameter (cm)	1.413	±0.226	1.359	±0.237	-3.8%	(0.15)	1.239	±0.186	1.227	±0.227	-1.0%	(0.72)
Mean cortical thickness (cm)	0.533	±0.059	0.532	±0.061	-0.2%	(0.94)	0.481	±0.052	0.453	±0.043	-5.7%	0.0024
CSMI (cm^4)	1.65	±0.313	1.544	±0.245	-6.4%	0.041	1.027	±0.191	0.939	±0.143	-8.6%	0.0074
Z (cm^3)	1.314	±0.172	1.249	±0.133	-4.9%	0.024	0.924	±0.121	0.860	±0.093	-6.9%	0.0024
Bone Strength Index (x100)	2.509	±0.336	2.333	±0.260	-7.0%	0.0016	1.815	±0.258	1.691	±0.223	-6.8%	0.0062
Thigh Lean Mass Fraction	0.884	±0.048	0.873	±0.063	-1.1%	(0.3)	0.764	±0.057	0.733	±0.056	-4.1%	0.0016
Thigh Muscle Cross-Sectional Area (cm^2)	204.5	±16.6	197.7	±20.5	-3.3%	0.018	168.9	±17.5	162.2	±11.9	-3.9%	0.033

† Values in parentheses not significant ($p > 0.05$, two tailed *t*-test).
* Tibial statistics exclude one male femoral fracture case (see text).

Table 4: Means and standard deviations of age, anthropometric dimensions and exercise scores broken down by ethnic group for males and female Marine Corp recruit subjects.

	MALES						FEMALES					
	Whites (n=425)		African-Americans (n=43)		Hispanics (n=133)		Whites (N=447)		African-Americans (N=119)		Hispanics (N=76)	
Parameter	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Age	19.2	±1.78	19.4	±1.95	19.2	±1.72	19.0	±1.95	19.2	±2.13	19.2	±2.06
Weight (kg)	76.1	±11.2	74.3	±10.2	72.6†	±10.6	58.4	±7.34	57.4	±7.16	56.4	±7.35
Height (cm)	176.3	±6.33	175.0*	±5.82	171.1†	±6.21	163.3	±6.37	163.8*	±5.95	158.6†	±6.00
BMI (kg/m^2)	24.4	±3.17	24.3	±3.20	24.8	±3.24	21.8	±2.12	21.4*	±2.07	22.4†	±1.92
Neck girth (cm)	38.7	±2.28	38.0	±2.19	38.3	±2.05	31.9	±1.52	32.0	±1.49	31.7	±1.47
Waist girth (cm)	85.2	±8.69	81.6†*	±7.41	85.5	±8.37	69.0	±5.24	67.5†*	±4.40	69.8†	±5.73
Hip girth (cm)	-	-	-	-	-	-	94.2	±5.44	93.6	±5.76	93.1	±5.70
Percent Body Fat	16.0	±5.60	13.9†*	±5.10	17.4†	±5.54	24.3	±4.32	23.2*†	±3.99	25.1	±4.53
Pelvic width (cm)	28.7	±2.45	27.2†	±2.18	28.1	±2.35	28.2	±1.90	26.7†	±1.97	27.6	±1.97
Trochanteric width (cm)	-	-	-	-	-	-	31.9	±1.85	31.0†	±1.96	31.0†	±1.96
Femur bicondylar breadth cm)	10.5	±0.77	10.5	±0.71	10.3	±0.79	8.97	±0.51	8.88	±0.52	8.85	±0.45
Thigh length (cm)	52.6	±2.74	54.0†*	±2.66	51.23†	±2.47	51.4	±3.09	52.4*†	±2.75	50.2†	±2.97
Tibia length (cm)	40.9	±2.22	42.2†*	±2.59	39.7†	±2.20	36.8	±2.14	38.5†*	±2.38	36.3	±2.21
Leg length (cm)	104.3	±4.80	105.8*	±4.76	101.0†	±4.63	87.7	±4.69	90.5†*	±4.48	86.4	±4.68
Thigh girth (cm)	54.6	±4.53	55.5*	±5.07	53.6†	±4.58	52.2	±4.25	52.4	±4.04	51.7	±3.90
Calf girth (cm)	37.6	±2.72	37.3	±3.00	36.3†	±2.42	34.8	±2.28	34.0†	±2.41	33.79†	±2.04
Numbers of sit-ups	57.9	±13.3	52.8	±12.9	56.5	±12.0	35.4	±7.00	35.3	±6.18	34.5	±6.28
Run-scores (seconds)	1090	±112	1113	±105	1081	±124	1215	±103	1251†	±116	1227	±97.2

† Significantly different from Whites by Tukey/Kramer post-hoc analysis ($p < 0.05$).
* Significantly different from Hispanics by Tukey/Kramer post-hoc analysis ($p < 0.05$).

Table 5: Height and weight corrected mean values of pelvic widths, bone lengths, geometric properties, BMD and muscle measurements broken down by sex and ethnic group.

	MALES						FEMALES					
	Whites (N=425)		African-Americans (N=43)		Hispanics (N=133)		Whites (N=447)		African-Americans (N=119)		Hispanics (N=76)	
Parameter	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Pelvic width (cm)	28.5	±2.058	27.3†*	±2.140	28.6	±1.946	28.1	±1.487	26.9*†	±1.717	27.9	±1.438
Femur bicondylar breadth cm)	10.43	±0.616	10.56	±0.537	10.42	±0.630	8.94	±0.387	8.91	±0.401	8.94	±0.352
Thigh length (cm)	52.0	±2.197	54.0†*	±2.042	52.3	±1.889	50.6	±2.152	51.6†	±2.106	51.6†	±2.156
Tibia length (cm)	40.5	±1.369	42.2†*	±1.670	40.8	±1.254	36.7	±1.240	38.2*†	±1.631	37.5†	±1.270
Tibia BMD (g/cm^2)	1.527	±0.120	1.563*	±0.125	1.504	±0.119	1.435	±0.140	1.465*†	±0.157	1.380†	±0.131
CSA (cm^2)	2.007	±0.189	2.096†*	±0.218	1.977	±0.186	1.629	±0.192	1.694*†	±0.200	1.603	±0.165
Periosteal diameter (cm)	2.167	±0.146	2.210	±0.168	2.165	±0.137	1.873	±0.132	1.909†	±0.146	1.911†	±0.135
Endosteal diameter (cm)	1.459	±0.184	1.485	±0.206	1.476	±0.172	1.192	±0.175	1.212	±0.201	1.268†	±0.178
Mean cortical thickness (cm)	0.353	±0.036	0.362*	±0.038	0.347	±0.036	0.341	±0.045	0.349*	±0.050	0.322†	±0.040
CSMI (cm^4)	0.782	±0.171	0.870†*	±0.217	0.779	±0.153	0.467	±0.113	0.509†	±0.120	0.482	±0.105
Z (cm^3)	0.713	±0.107	0.773†*	±0.133	0.710	±0.100	0.492	±0.085	0.527*†	±0.090	0.497	±0.077
Bone Strength Index	1.759	±0.263	1.834	±0.321	1.738	±0.256	1.336	±0.226	1.375	±0.231	1.327	±0.211
Femur BMD (g/cm^2)	2.158	±0.158	2.181	±0.167	2.135	±0.163	1.937	±0.135	1.929	±0.172	1.891†	±0.128
CSA (cm^2)	3.249	±0.289	3.306*	±0.230	3.175†	±0.270	2.580	±0.227	2.584	±0.253	2.510†	±0.196
Periosteal diameter (cm)	2.480	±0.155	2.502	±0.161	2.449	±0.153	2.197	±0.130	2.209	±0.123	2.185	±0.101
Endosteal diameter (cm)	1.415	±0.223	1.419	±0.268	1.393	±0.232	1.234	±0.193	1.252	±0.203	1.255	±0.152
Mean cortical thickness (cm)	0.533	±0.058	0.542	±0.066	0.529	±0.061	0.480	±0.049	0.478	±0.063	0.465†	±0.044
CSMI (cm^4)	1.651	±0.322	1.728*	±0.297	1.585	±0.278	1.020	±0.195	1.041	±0.188	0.990	±0.131
Z (cm^3)	1.314	±0.175	1.362*	±0.157	1.276	±0.158	0.918	±0.123	0.934	±0.122	0.895	±0.088
Bone Strength Index	2.522	±0.345	2.526	±0.285	2.436†	±0.313	1.814	±0.265	1.813	±0.253	1.734†	±0.189
Thigh Lean Mass Fraction	0.884	±0.049	0.905†*	±0.035	0.874†	±0.045	0.773	±0.046	0.811*†	±0.042	0.771	±0.047
Thigh Muscle Cross-Sectional Area (cm^2)	204	±16.4	221†*	±18.2	199†	±14.4	167	±14.4	180*†	±17.2	163	±15.7

† Significantly different from whites by Tukey/Kramer post-hoc analysis (p <0.05).
* Significantly different from Hispanics by Tukey/Kramer post-hoc analysis (p <0.05).

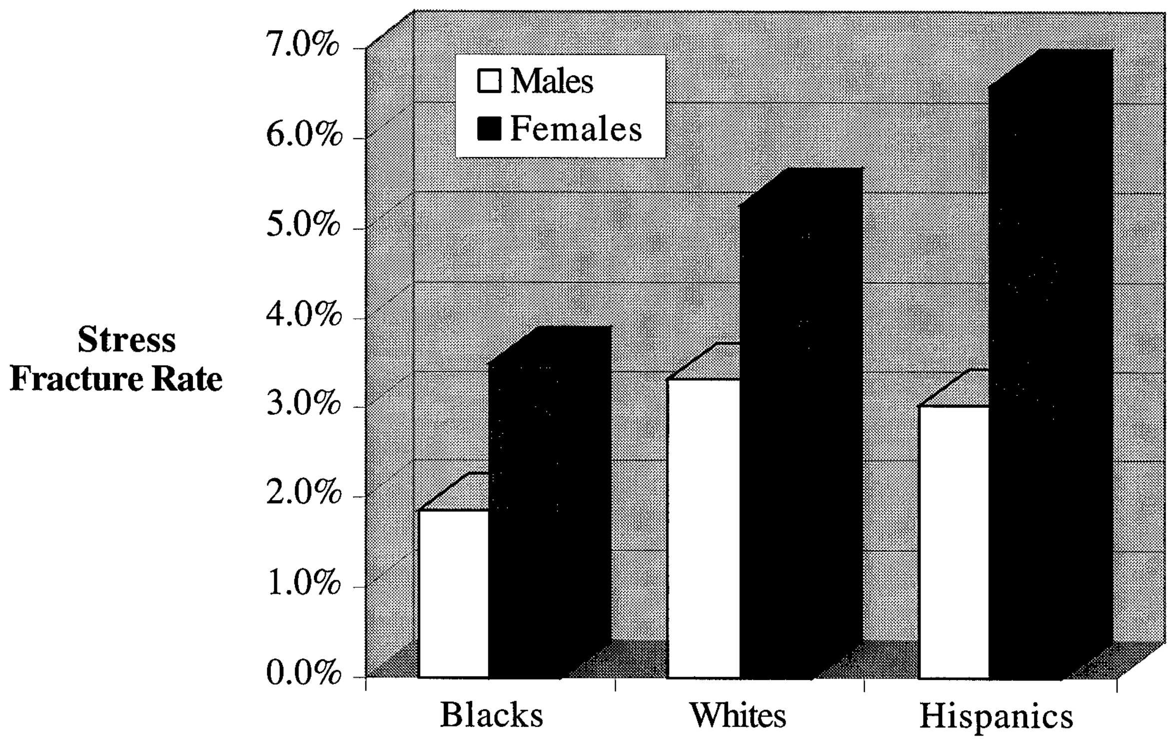

Figure 1: The rates of stress fractures in US Marine Corps Recruits broken down by sex and ethnic group (see text).

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PERSONNEL

The personnel who were partially or completely supported in this project included:

Thomas J. Beck, Sc.D., Principle Investigator

Christopher B. Ruff, Ph.D. Co-Investigator

Daniel W. Trone, M.A., (Through subcontract with Naval Health Research Center, San Diego, others including students also supported.)

Kelli Betsinger, B.A., Project manager and coordinator at Parris Island Marine Corps Recruit Training Depot.

Other Parris Island workers:
Myriam Miller
Marsha Christopher
Elizabeth Tiglao
John Norman
Dione Silva

Mary Durm, B.A., Project manager and coordinator, prior to Kelli Betsinger. She left the project when her husband was transferred.

Kellie Leatherman, B. A., performed data entry and budget management.

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